Synchrotron Radiation in Interaction Region

and comment on BBREM rad. Bhabha lifetime

by **Helmut Burkhardt** (CERN) for the FCC-ee-MDI team
with **Manuela Boscolo** (INFN-LNF)
and **Nicola Bacchetta** (INFN) for detector/experiments

More on MDI for FCC-ee, concepts and generic simulations :

Principles and scaling	**presentation by Manuela**	**Oct. '13**	**at**	**TLEP#6**	**CERN**
Experience with backgrounds	**presentation by Helmut**	**March' 14**	**at**	**EIC'14**	**JLAB**
MDI for FCC-ee	**presentation by Nicola**	**June '14**	**at**	**TLEP#7**	**CERN**
Losses in IR and Touschek	**presentation by Manuela**	**Oct.'14**	**at**	**HF2014**	**Beijing**
Interaction Region Challenges	**presentation by Helmut**	**Oct.'14**	**at**	**TLEP#8**	**Paris via Vidyo**
Synchr. Rad. in IR	**presentation by Helmut**	**Dec.'14**	**at**	**FCC-ee-Acc#11**,	**CERN**
Progress in SR and tools	**presentation by Manuela**	**Feb'15**	**at**	**TLEP#9**	**Pisa**
Losses in IR region	**presentation by Manuela**	**later today**	**at**	**FCC 2015**	**Washington**

BBBREM rad. Bhabha lifetime

Total e+e-(γ) cross-section relevant for beam lifetime, dominated by very forward rad. Bhabha
For free e+e and s_b = 2% energy acceptance (bucket height)
σ = 0.278 barn   Eb = 120 GeV
σ = 0.285 barn   Eb = 175 GeV

$$\sigma = \int_{s_b}^{1} \frac{d\sigma}{dk} = \frac{16}{3}\alpha r_e^2 \left[\left(-\log s_b - \frac{5}{8}\right) \left(\log(4\gamma_e^+\gamma_e^-) - \frac{1}{2}\right) + \frac{\log^2 s_b}{2} - \frac{3}{8} - \frac{\pi^2}{6} \right]$$

Actual machine : particles confined to bunches
no collisions with very small momentum transfer corresponding to distances larger than
d = beam height at collisions (and distance between particles)
Fully simulated (to first order with single photon emission, accurate cross section and spectra)
in BBBREM on event by event basis with
t_{max} = (hbarc / dist)^2, reject t > t_{max} (hard cutoff) or reduce weight $t^2/(t-t_{max})^2$ (soft cutoff)

With cutoff, the cross section becomes ~ independent of beam energy
for s_b = 2% and d in the range of 0.1 - 1 mm (log. dependence on cutoff)
reduced to σ = 0.15 barn, or nearly doubling the lifetime !

References :

BBBREM, R.Kleiss and H.B. , Comp.Phys. Comm. 1994
Altarelli, Buccella, Nuovo Cimento 34 (1964) 1337
H.B., R. Kleiss, Beam Lifetimes in LEP, Proc. EPAC 1994
G.L.Kotkin, V.G. Serbo, Beam-size effect, PRSTAB 2004, JINST 2009

IR design, goal and key points

Goal : maximizing performance (integrated luminosity) for experiments for good or at least tolerable experimental (background, stability) conditions.

Some key points :

Minimize synchrotron radiation in the IR region :

Bends as weak as possible and as far as possible from IP

difficult with large crossing angle and local chromaticity correction

difficult to optimize in single design for Z and top energy

Quads have to be strong and close to IP.

Minimize offset from quad axis

Careful with vertical halo/tails

Profit from

- LEP and e+e- factory design experience
- Progress in technology and computing

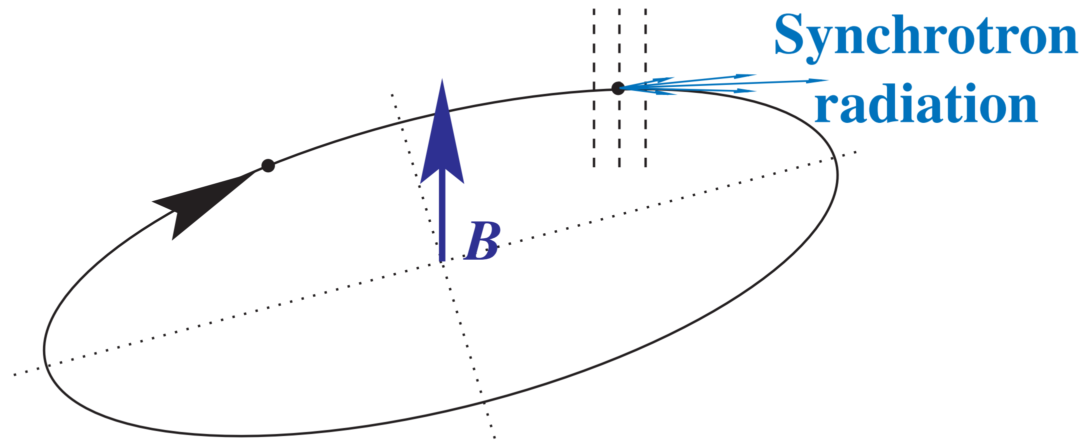
Synchrotron radiation

$$E_c = \frac{3}{2}\,\frac{\hbar c\,\gamma^3}{\rho} = 2.96\times 10^{-7}\mathrm{eV\,m}\;\frac{\gamma^3}{\rho}$$

$$\langle E_\gamma \rangle = \frac{8}{15\sqrt{3}}\,E_c \approx 0.308\;E_c$$

$$U_0 = \frac{e^2}{3\epsilon_0}\,\frac{\gamma^4}{\rho} \approx 6.0317\cdot 10^{-9}\;\mathrm{eV\;m}\quad \frac{\gamma^4}{\rho}$$

$$P_b = \frac{U_0\,I_b}{e}$$



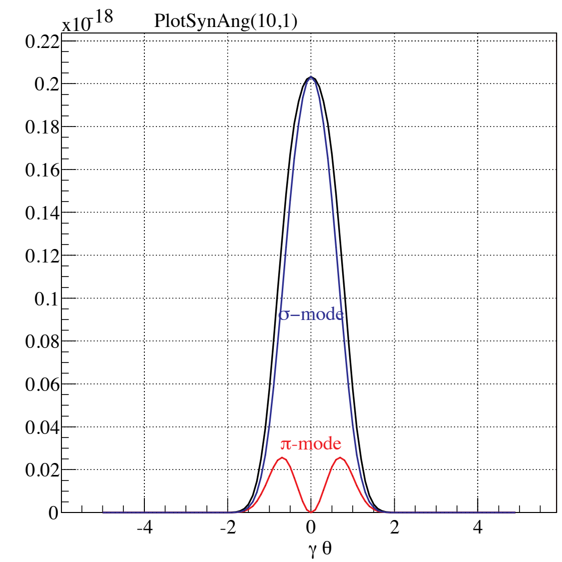
mean free path length λ between radiation

$$\lambda = \frac{\lambda_B}{B_\perp} \qquad \text{where} \quad \lambda_B = \frac{2\sqrt{3}}{5}\,\frac{m\,c}{\alpha\,e} = 0.16183\,\mathrm{Tm}$$

LEP2, FCC-ee, B ≃ O (0.1 T) O (1 m)

SynRad cone distribution mostly from bending angle O(mrad)

+ minor contribution from
beam divergence O(10 μrad)
and SynRad process



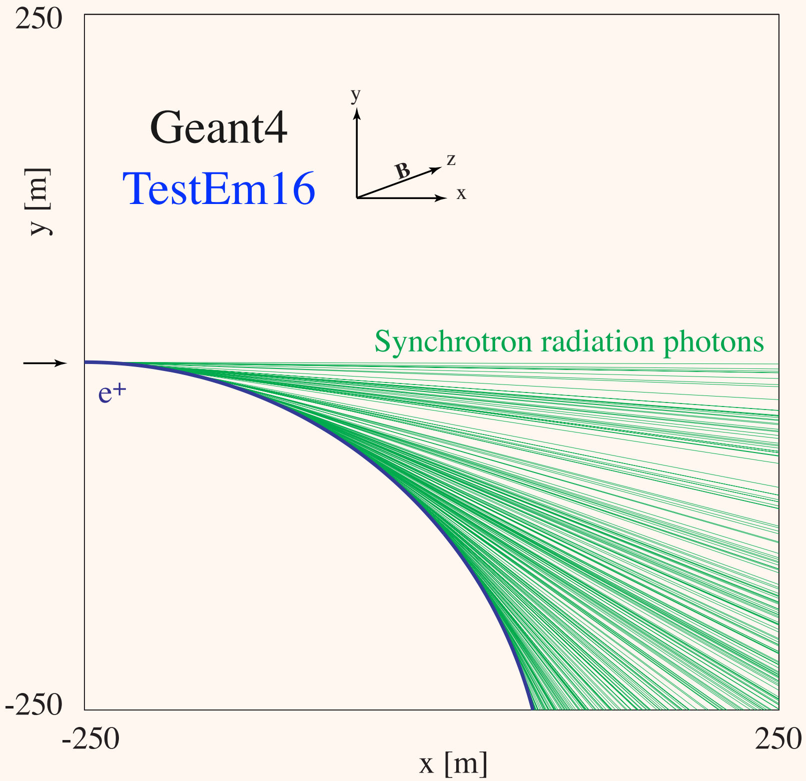
angular distribution (at E_c)
~ 1/γ = 3 μrad @ 175 GeV

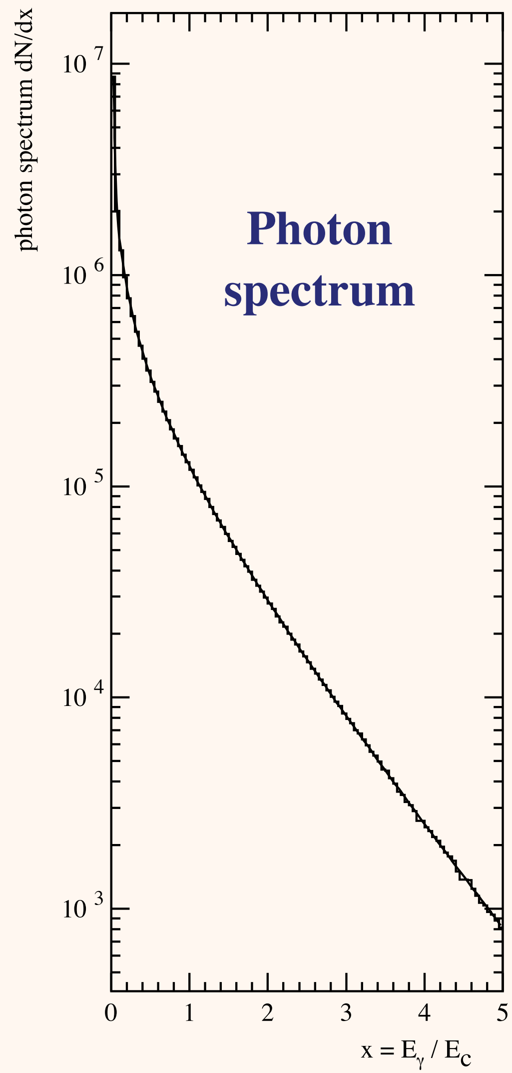
Spectrum

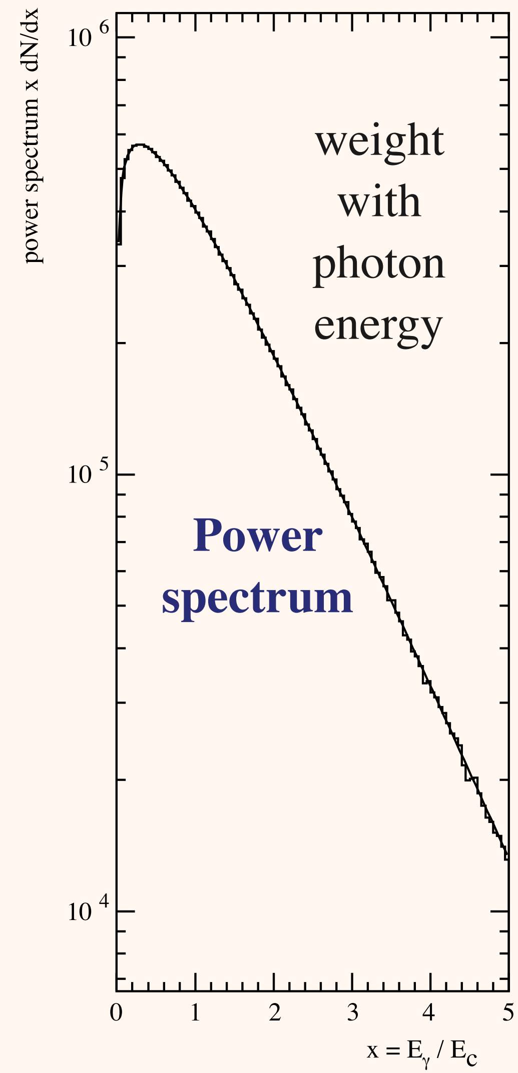
Photon energy in units of the critical energy. $x = E_\gamma / E_c$

For hom. field over formation length : single spectrum

$$\frac{d^2N}{ds\,dx} = \frac{\sqrt{3}\,\alpha}{2\pi}\,\frac{eB_\perp}{mc}\int_x^\infty K_{5/3}(\xi)\,d\xi$$







10 GeV e+ moving initially in x-direction, bend downwards on a circular path by a 0.1 T magnetic field in z-direction. Geant4 TestEm16

Recently generalized to all long live charged particles including ions

in Geant4 10.1 released 5/12/2014

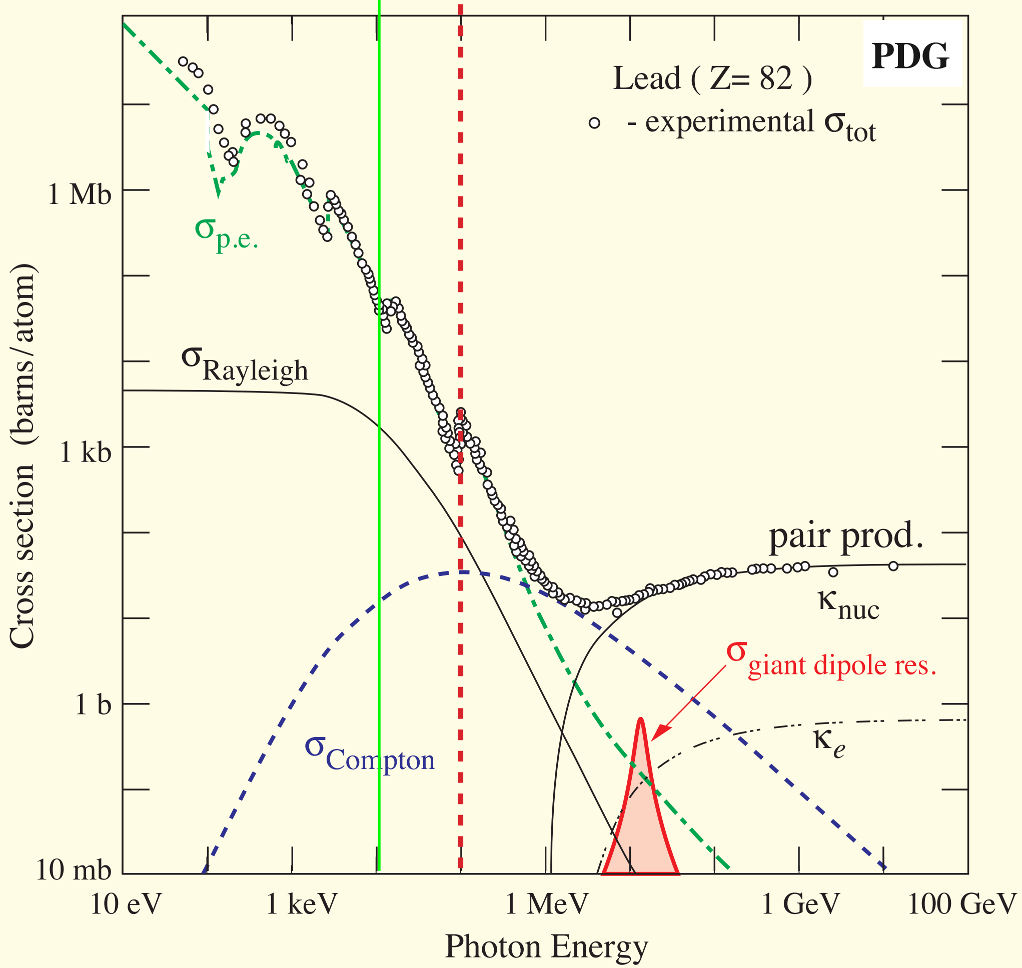
Ref. : H.B., CERN-OPEN-2007-018, Geant4 physics-manual Implemented as process G4SynchrotronRadiation

Spectrum and absorption

✔ < 10 keV

> 100 keV very difficult

10 MeV significant neutron flux, giant dipole res.



Critical photon energies

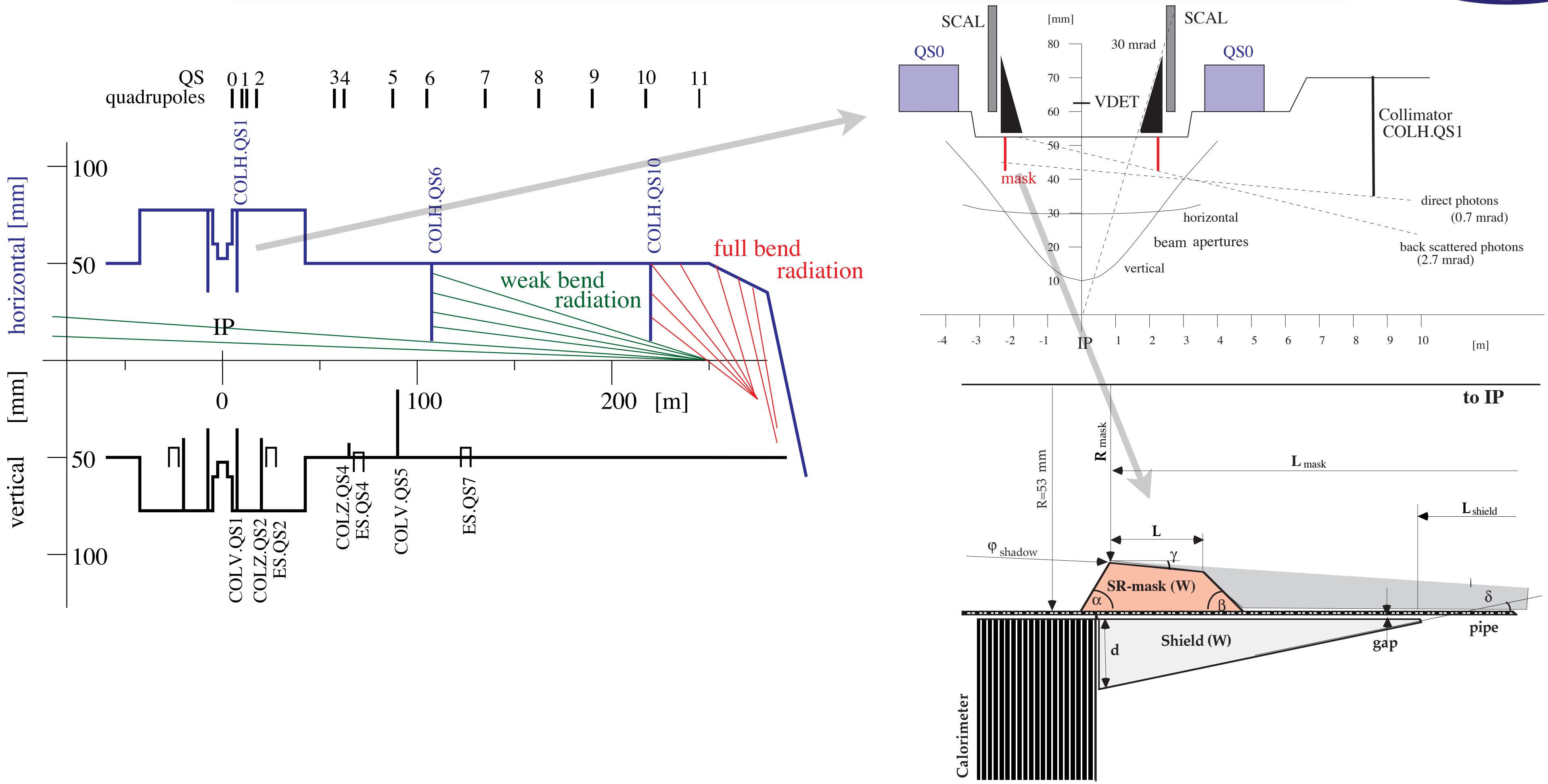
SuperKEKB ~ 2 keV (LER)
FCC-hh ~ 5 keV

LEP1 : 69 keV
LEP2 : 724 keV (arc, last bend 10× lower)

TLEP : ~ 350 keV (arc, 175 GeV)
similar to LEP2
Enormous photon flux, MWs of power
can get kW locally, melt equipment, detectors
Very difficult but not impossible as demonstrated in LEP2

as long as no hard synchrotron radiation is generated towards experiments in the IR !!

LEP, as example of an IR optimized for SR



Eb = 45 GeV to 105 GeV **the closest we got to FCC-ee**

Machine induced backgrounds, MIB in LEP **~ 100 collimators to reduce MIB**

flat, symmetric machine, no crossing angle, few (4-12) bunches

Synchrotron radiation - **no direct and single reflected radiation to experiments in IP region**

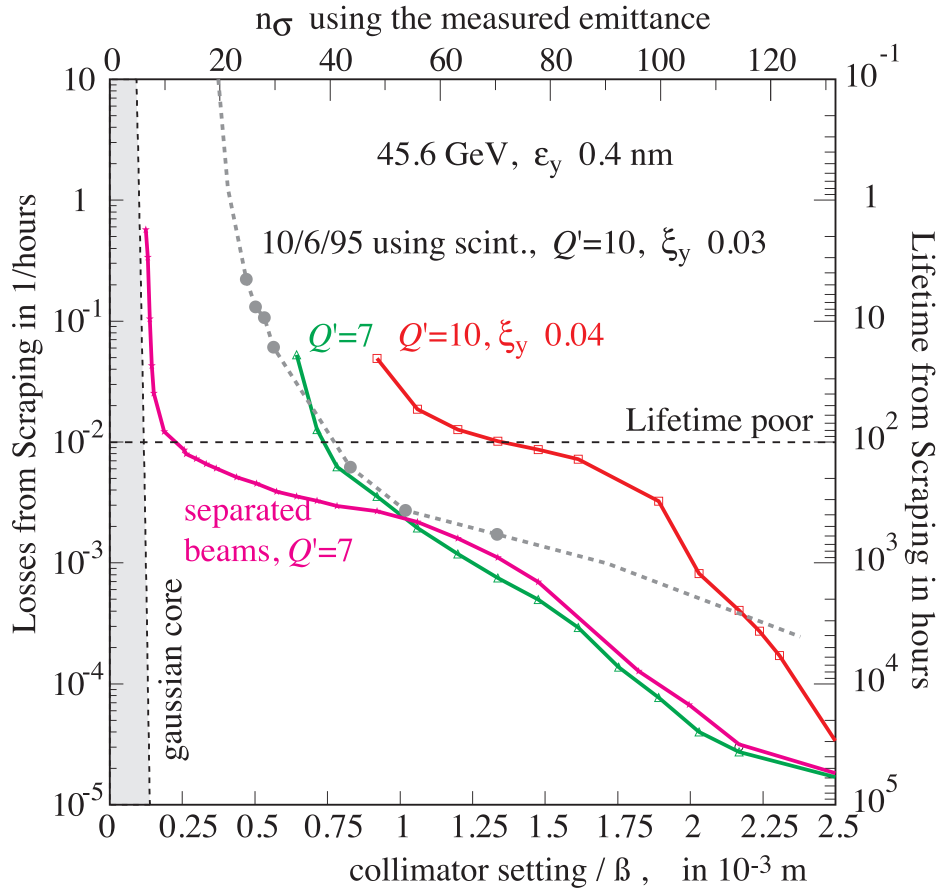
Off-momentum beam-gas and thermal photon

G. von Holtey at al., Nucl.Instrum.Meth.A403:205-246, 1998

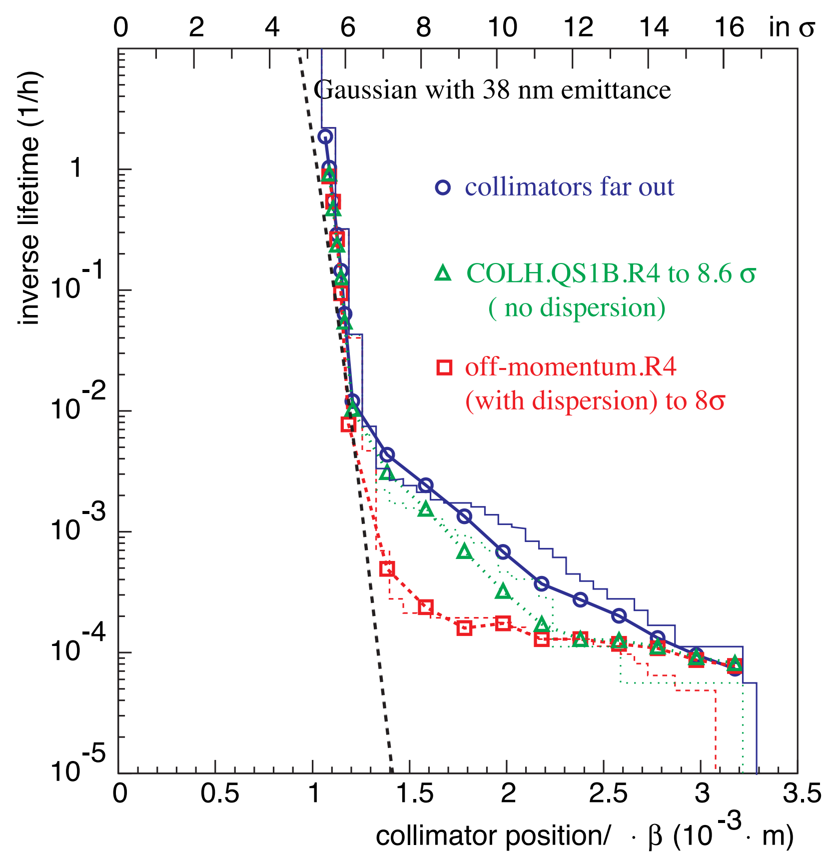
non-Gaussian tails, LEP

measured by scraping with loss monitors

vertical plane, colliding beams



horizontal plane
reproduced by simulation



Tails from : beam-beam, high chromaticity, particle scattering

Background spikes, enhanced synchrotron radiation from quadruples

H. Burkhardt, "BEAM LIFETIME AND BEAM TAILS IN LEP." CERN-SL-99-061-AP and Proc. e+ e+ Factories 1999, KEK, Tsukuba 1999
Transverse beam tails due to inelastic scattering, Phys. Rev. ST Accel. Beams 3, 091001 (2000)

Generic tool MDISim

Basis : MAD-X lattice and survey (geometry) description, if available with apertures

ROOT as main geometry and interface tool

With extra library to read MAD-X tfs files and calculate derived machine parameters (SynRad)

Step 1 : Construct tables (ntuples) with detailed information element by element

transformation of Courant-Snyder machine coordinates to Euclidian detector coordinates

optionally scale up transverse dimensions

```
NtupleRoot nt_b1( ReadAndMerge(Optics_tfs,Survey_tfs) ; // Optics and survey tfs tables from MAD-X
Beam b1(Optics_tfs); // get Energy and synchr integrals from optics twiss header
double nsig=1;    // quad radiation from sawtooth + beam size.  0 is sawtooth only
EmitRatio=0.001;  // as a start
CalcBeamSizeDivergence(nt_b1,b1.ex,b1.ey,verbose); // calculate beam sizes and divergences and add to ntuple
CalcSynrad(nt_b1,b1,verbose,nsig); // calculate synchrotron radiation for bends and quads
```

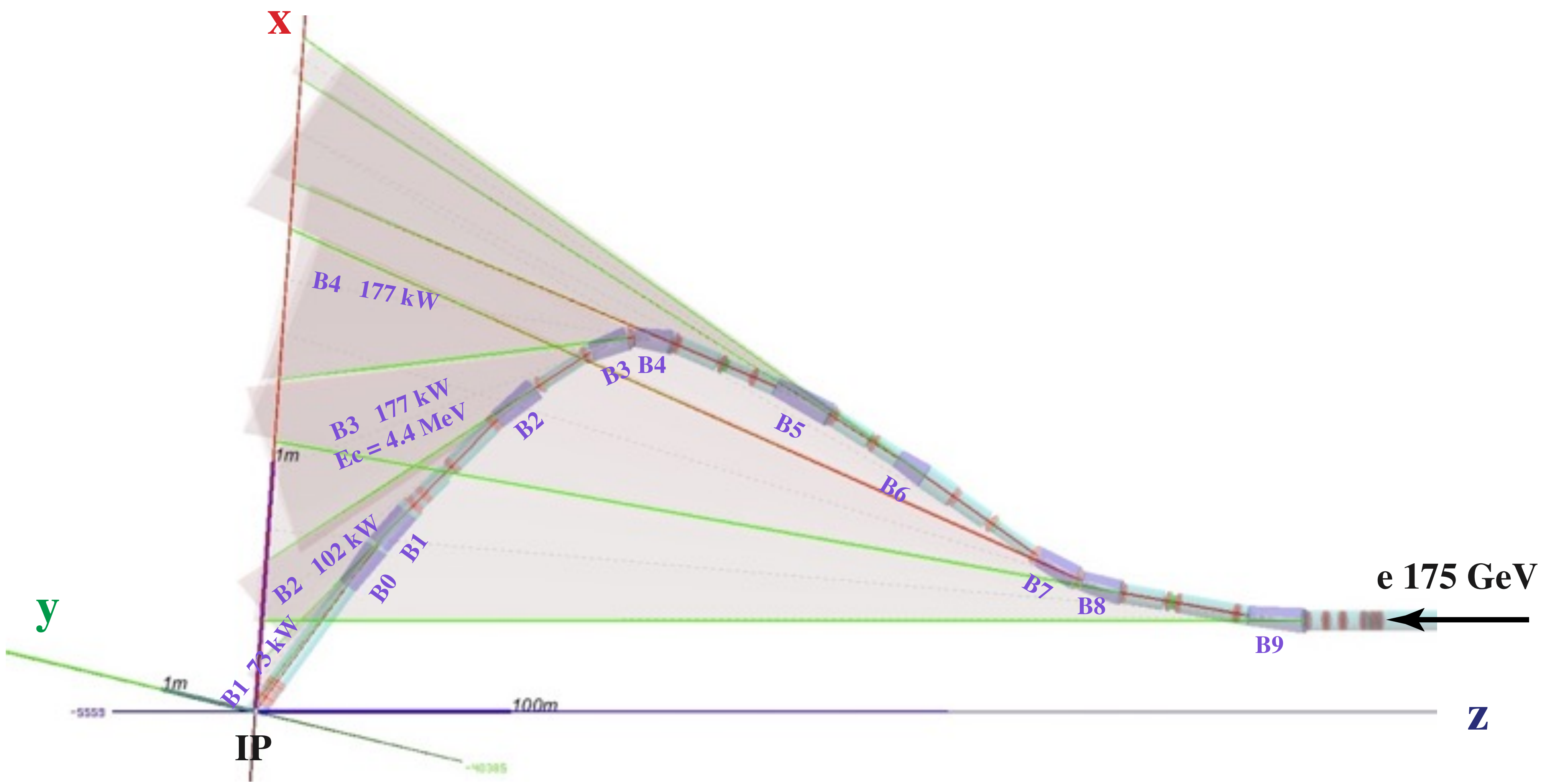
Step 2 : visualize geometry using root, look at S.R. cones

```
Ntuple2Geom ; // construct geometry in root, export in various formats, root, gdml..
StartEveWithGeomDisplay(ResolveHome("~/www/Geom/TLEP_V14_IR_6_14_3.root"));
Plot_Bend_SR_Cones(nt_b1,b1,zmin,zmax,Scale_xy,verbose,goto_CM_units,-1);
```

Step 3 : tracking and shower Monte Carlo, various options, import geometry to Geant4 (via SGML) or BDSIM..

SynRad bend cones for TLEP_V14_IR_6-13-2 BINP IR

MDISIM/root/ 3d-OGL display



Synchrotron radiation into IR major challenge : **0.6 MW** / beam of MeV γ's into detector region

TLEP V14 IR 6-14-3 BINP

Optics files from /afs/cern.ch/eng/fcc/ee/TLEP_V14_IR_6-14-3 by Anton Bogomyagkov et al. from 2/5/2015
as presented by Anton 9/2/2015 at CERN, see indico **NEW** : was no ring, only 1/4 patched by me to make a ring

iele	NAME	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV
		m	m		keV		m	T	m	mm	mrad	kW	
13	L.MB0	43.5	10.5	0.001	1132	3.607	10500.0	0.0556	60.2966	0.2771	0.0130	8.085	1.e-05
15	L.MB1	55	10.5	0.003	3397	10.82	3500.0	0.1668	16.9198	0.1468	0.0130	72.76	0.007505
39	L.MB2	104.2	14.5	0.004167	3416	15.03	3480.0	0.1677	22.4885	0.1692	0.0105	101.6	0.007653
59	L.MB3	141.7	15	0.005586	4428	20.15	2685.1	0.2174	6.8157	0.0932	0.0151	176.6	0.01695
65	L.MB4	159.5	15	0.005586	4428	20.15	2685.1	0.2174	63.5433	0.2844	0.0152	176.6	0.01695
91	L.MB5	224	21.5	0.002202	1218	7.943	9763.7	0.0598	20.1852	0.1603	0.0083	19.2	2.e-05
105	L.MB6	262.5	10.5	0.0007305	827.1	2.635	14373.7	0.0406	34.6148	0.2099	0.0061	4.314	4.e-07
129	L.MB7	321.8	14.5	-0.00273	2238	9.847	5311.4	-0.1099	16.4972	0.1449	0.0104	43.63	0.001329
135	L.MB8	339.1	14.5	-0.00273	2238	9.847	5311.4	-0.1099	15.8610	0.1421	0.0105	43.63	0.001329
165	L.MB9	411.4	21.5	-0.001812	1002	6.536	11864.8	-0.0492	37.2633	0.2178	0.0097	12.97	4.e-06
253	MB1.A1C1.DS	640.5	10.5	0.0004884	553	1.762	21497.4	0.0272	36.5415	0.2157	0.0093	1.929	8.e-10
255	MB2.A1C1.DS	651.6	10.5	0.0004884	553	1.762	21497.4	0.0272	17.8663	0.1508	0.0093	1.929	8.e-10

PowSum = 54.53 MW bends full ring. 0.6 MW within 250 m to IP

Quads, at 1 sigmax, horizontal

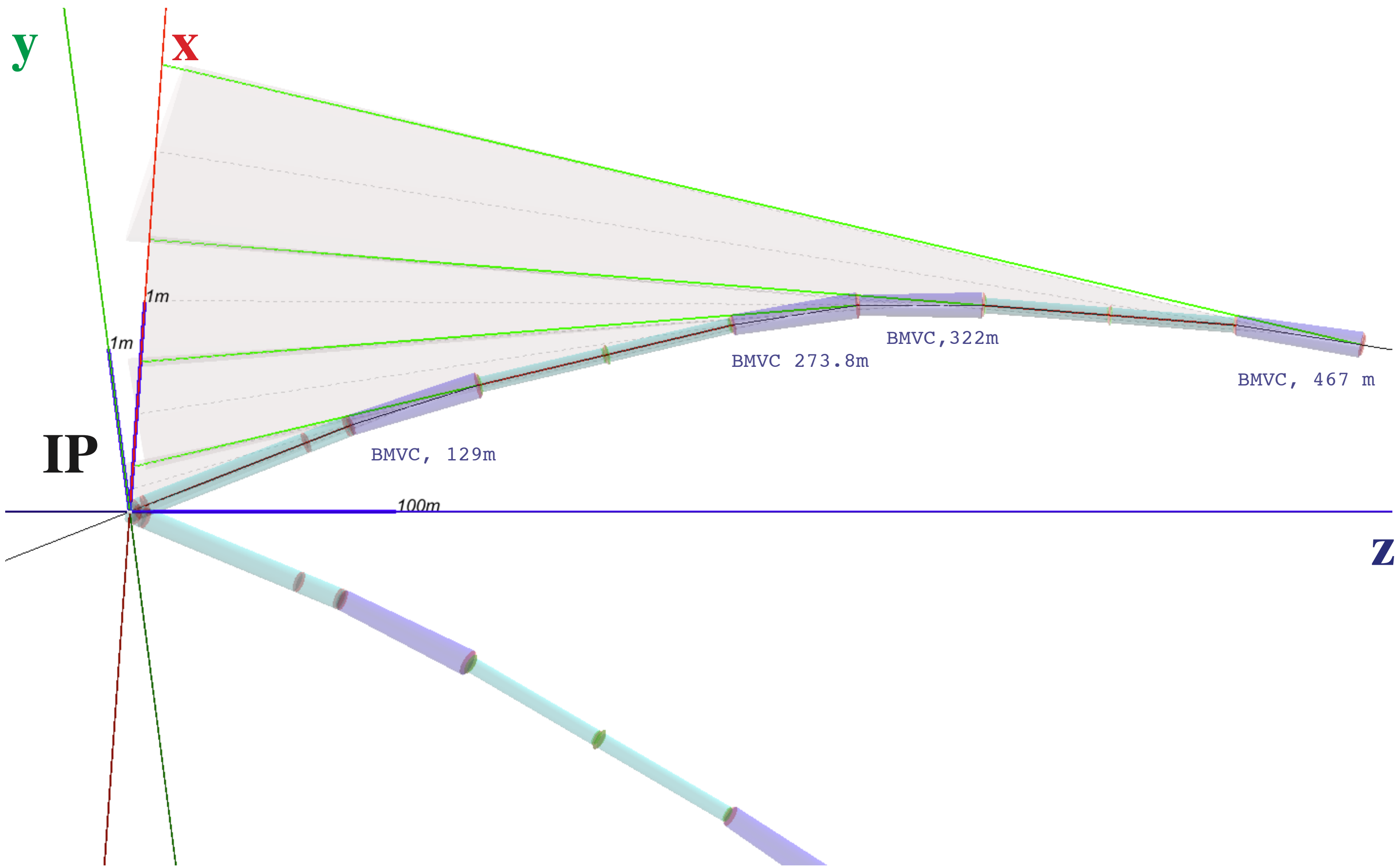
iele	Element	s	L	betx	sigx	divx	K1L	k0	x	Angle	Ecrit	ngam	Power
		m	m	m	mm	mrad	m-2	m-1	mm		keV		kW
6	L.MQ0_1	3.8	1.8	1.01e+04	0.3156	3.131e-05	-0.2848	9.311e-05	0.01133	0.0001676	1107	0.6045	1.325
8	L.MQ0_2	5.6	1.8	7.73e+03	0.2763	3.576e-05	-0.2848	8.548e-05	0.02379	0.0001539	1016	0.555	1.116
10	L.MQ1_1	7	1	4.16e+03	0.2029	4.871e-05	0.1502	3.573e-05	0.03497	3.573e-05	424.8	0.1289	0.1084
12	L.MQ1_2	8	1	3.51e+03	0.1862	5.307e-05	0.1502	3.355e-05	0.03711	3.355e-05	398.9	0.121	0.09555
18	L.MQ2_1	58	1	408	0.06351	0.0001556	-0.04789	3.253e-06	0.004413	3.253e-06	38.67	0.01173	0.0008981
20	L.MQ2_2	59	1	323	0.05647	0.000175	-0.04789	2.893e-06	0.003951	2.893e-06	34.4	0.01044	0.0007106

red color : critical energy over 100 keV, Power > 1kW and within 250 m of IP

Looking at one beam, 0 - 500 m right of IR

x, y scales × 100

MDISIM/root/ 3d-OGL display



TLEP_V12A CERN

Based on tlep_v12a_cern_full_ring.madx from Roman Martin received by email on 10/12/2014

iele	NAME	KEYWORD	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV
			m	m		keV		m	T	m	mm	mrad	kW	
14	BMVC	SBEND	129	47.26	0.002	503.1	7.214	23629.2	0.0247	315.4373	0.5597	0.0056	7.368	1.3e-10
24	BMVC	SBEND	273.8	47.26	0.002	503.1	7.214	23629.2	0.0247	101.8127	0.3180	0.0056	7.368	1.3e-10
26	BMVC	SBEND	322.1	47.26	0.002	503.1	7.214	23629.2	0.0247	315.4341	0.5597	0.0056	7.368	1.3e-10
36	BMVC	SBEND	466.8	47.26	0.002	503.1	7.214	23629.2	0.0247	101.8127	0.3180	0.0056	7.368	1.3e-10
39	BMHC	SBEND	503	35.19	-0.002	675.6	7.214	17596.9	-0.0332	21.7132	0.1468	0.0070	9.893	2.3e-08
49	BMHC	SBEND	611.6	35.19	-0.002	675.6	7.214	17596.9	-0.0332	100.0721	0.3153	0.0070	9.893	2.3e-08
51	BMHC	SBEND	647.8	35.19	-0.002	675.6	7.214	17596.9	-0.0332	21.7132	0.1468	0.0070	9.893	2.3e-08
61	BMHC	SBEND	756.4	35.19	-0.002	675.6	7.214	17596.9	-0.0332	100.0721	0.3153	0.0070	9.893	2.3e-08
79	MB1.A3C1.DS	SBEND	808.8	10.5	0.0004958	561.4	1.789	21176.5	0.0276	36.2019	0.1896	0.0082	2.038	1.1e-09
81	MB2.A3C1.DS	SBEND	819.9	10.5	0.0004958	561.4	1.789	21176.5	0.0276	17.5910	0.1322	0.0082	2.038	1.1e-09
88	MB3.A3C1.DS	SBEND	833.8	10.5	0.0004958	561.4	1.789	21176.5	0.0276	36.2604	0.1898	0.0082	2.038	1.1e-09
90	MB4.A3C1.DS	SBEND	844.9	10.5	0.0004958	561.4	1.789	21176.5	0.0276	71.8237	0.2671	0.0082	2.038	1.1e-09
98	MB5.A3C2.DS	SBEND	858.8	10.5	0.0004958	561.4	1.789	21176.5	0.0276	35.4975	0.1878	0.0083	2.038	1.1e-09
100	MB6.A3C2.DS	SBEND	869.9	10.5	0.0004958	561.4	1.789	21176.5	0.0276	17.0396	0.1301	0.0083	2.038	1.1e-09
107	MB7.A3C2.DS	SBEND	883.8	10.5	0.0004958	561.4	1.789	21176.5	0.0276	36.3660	0.1900	0.0084	2.038	1.1e-09
109	MB8.A3C2.DS	SBEND	894.9	10.5	0.0004958	561.4	1.789	21176.5	0.0276	73.1527	0.2695	0.0084	2.038	1.1e-09

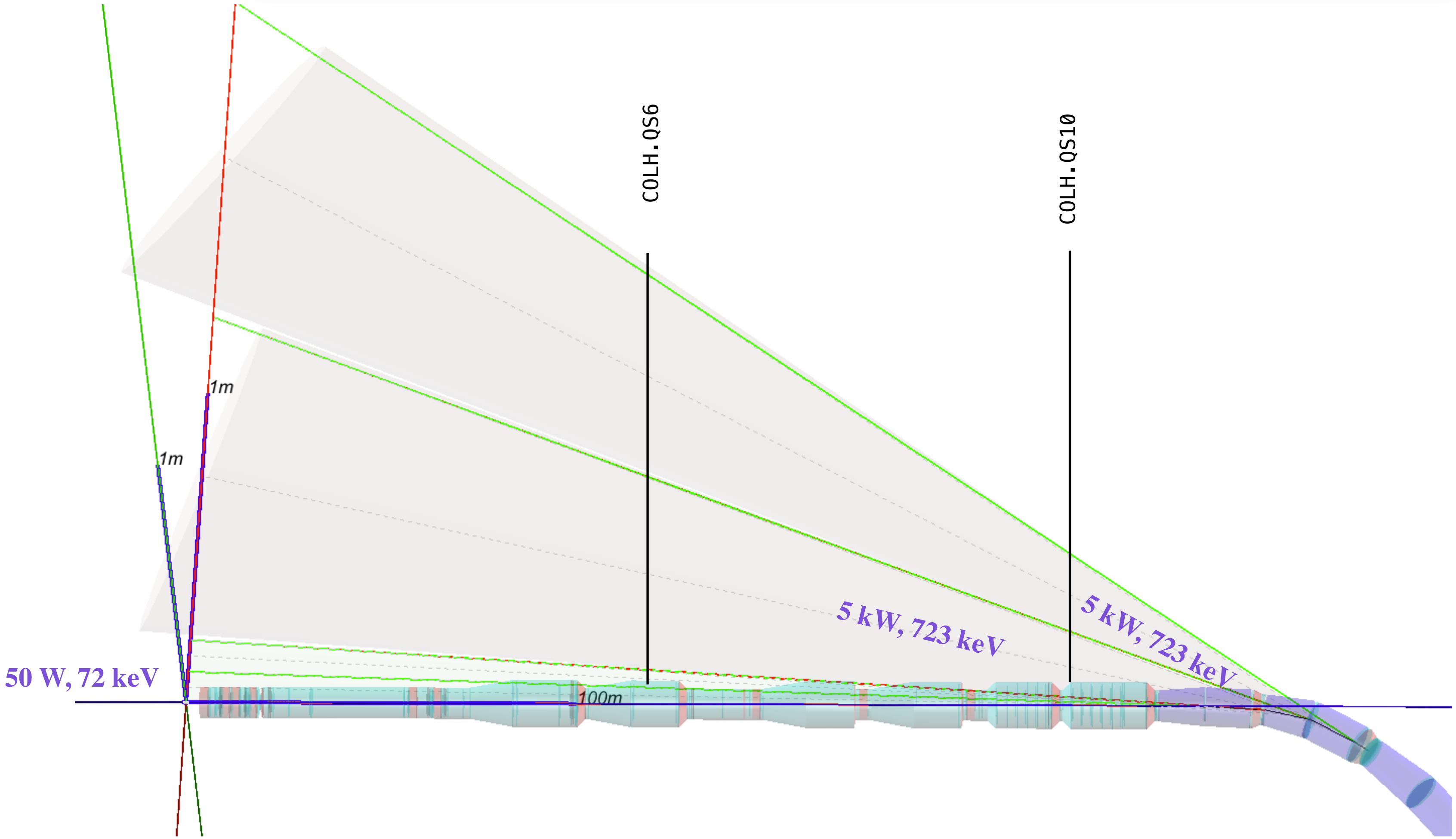
7.4 kW within 250 m to IP

Quads, at 1 sigmax, horizontal

iele	Element	s	L	betx	sigx	divx	K1L	k0	x	Angle	Ecrit	ngam	Power
		m	m	m	mm	mrad	m-2	m-1	mm		keV		kW
3	Q4	3.07	1.07	16.7	0.129	0.007701	-0.6072	7.83e-05	3.92e-21	8.41e-05	930.9	0.3034	0.5733
5	Q3	6.31	1.24	127	0.3545	0.002801	0.2751	9.752e-05	1.391e-20	0.0001204	1159	0.4345	1.022
8	Q2	65.4	1	28.7	0.1688	0.005882	-0.03894	6.575e-06	2.412e-20	6.575e-06	78.17	0.02372	0.003763
10	Q1	80.8	1	101	0.3168	0.003135	0.03318	1.051e-05	4.014e-20	1.051e-05	125	0.03792	0.009618
13	QDV	81.8	0.5	102	0.318	0.003123	-0.01475	4.692e-06	4.005e-20	2.346e-06	55.78	0.008462	0.0009581
15	QFV2	130	1	312	0.5568	0.001784	0.02951	1.643e-05	5.302e-18	1.643e-05	195.3	0.05927	0.0235
19	QDV2	178	1	8.04	0.08934	0.01112	-0.02951	2.636e-06	8.399e-18	2.636e-06	31.34	0.009509	0.000605
23	QFV2	227	1	315	0.5597	0.001774	0.02951	1.652e-05	2.284e-17	1.652e-05	196.4	0.05958	0.02375
25	QDV2	275	1	102	0.318	0.003123	-0.02951	9.384e-06	1.046e-17	9.384e-06	111.6	0.03385	0.007664

red color : critical energy over 100 keV, Power > 1kW and within 250 m of IP

LEP 100 GEV



iele	NAME	KEYWORD	S	L	Angle	Ecrit	ngamBend	rho	B	BETX	SIGX	divx	Power	frac>10MeV
			m	m		keV		m	T	m	mm	mrad	kW	
162	BW3.QS11.R2	RBEND	260.2	11.55	0.0003768	72.37	0.7767	30652.0	0.0109	45.5834	1.4262	0.0379	0.04989	2e-62
164	BW4.QS12.R2	RBEND	272.1	11.55	0.0003768	72.37	0.7767	30652.0	0.0109	33.8668	1.2293	0.0379	0.04989	2e-62
172	B2L.QS12.R2	RBEND	287.3	11.55	0.003768	723.7	7.767	3065.2	0.1088	88.0931	1.9827	0.0637	4.989	6.5e-08
174	B2R.QS13.R2	RBEND	299.2	11.55	0.003768	723.7	7.767	3065.2	0.1088	163.5957	2.7019	0.0636	4.989	6.5e-08

Quads, at 1 sigmax, horizontal

iele	Element	s	L	betx	sigx	divx	K1L	k0	x	Angle	Ecrit	ngam	Power
		m	m	m	mm	mrad	m-2	m-1	mm		keV		kW
2	QS0.R2	5.7	2	27.8	1.115	0.04003	-0.327	0.0003474	-0.0524	0.0006948	770.7	1.432	0.9798
10	QS1B.R2	11.2	2	226	3.176	0.01405	0.06314	0.0001918	-0.1377	0.0003836	425.5	0.7907	0.2987
12	QS1A.R2	13.7	2	278	3.523	0.01267	0.06314	0.0002129	-0.1509	0.0004259	472.4	0.8778	0.3681
20	QS2.R2	18	1.6	276	3.507	0.01272	0.01788	6.006e-05	-0.1471	9.61e-05	133.2	0.1981	0.023423
36	QS3.R2	59	2	39.4	1.326	0.03366	0.01879	2.45e-05	-0.02171	4.9e-05	54.35	0.101	0.004873

Conclusion

Keeping synchrotron radiation at tolerable level in the IR regions of FCC-ee is very challenging

Photon energies and power comparable to LEP2
where S.R. backgrounds in the IR were acceptable with weak bends, far from IR and using ~100 collimators and local masks, (L ~ 1.e32cm-2s-1)

High luminosity low energy e+e- factory inspired FCC-ee IR designs with large crossing angle and local chromaticity correction tend to generate too high S.R. power and energy

High energy e+e-
Need for optics and layout which simultaneously optimize luminosity and keep synchrotron radiation at tolerable levels

Backup

Export/import Geometry; ROOT to Geant4

ROOT

gGeoManager->Export("Geom.gdml"); // export the whole geometry in gdml, or xml, C, root

GEANT4, straightforward to import ROOT geometry - which can be full machine

```
   in DetectorConstruction.cc
G4GDMLParser parser ; parser.Read("FCC-hh.gdml");
fBox=parser.GetWorldVolume();
```

Loop over imported volumes and set magnetic field and additional parameters if required

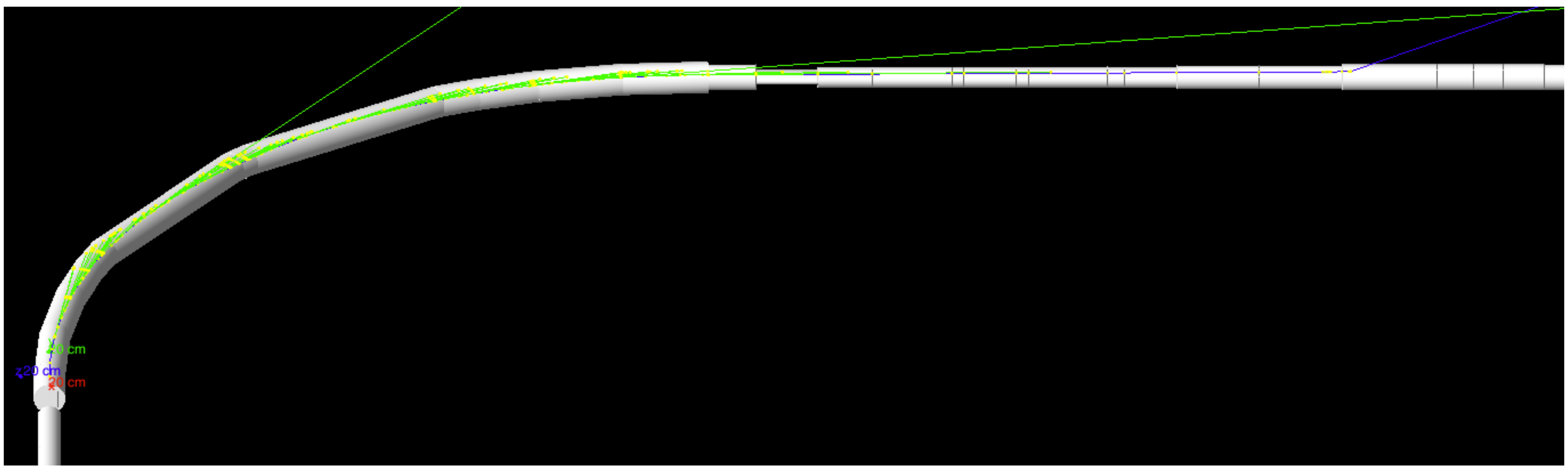
```
G4LogicalVolumeStore* lvs = G4LogicalVolumeStore::GetInstance();
for( auto lvciter = lvs->begin(); lvciter != lvs->end(); ++lvciter ) // loop over imported geometry modules
{
  G4MagField* ThisField = new G4MagField(localfieldValue); // set the local field
  G4FieldManager* fLocalFieldManager = new G4FieldManager(ThisField);
  fLocalFieldManager->SetDetectorField(ThisField);
  if(localfieldValue!=0)
  {
    fLocalFieldManager->CreateChordFinder(ThisField);
    fLocalFieldManager->GetChordFinder()->SetDeltaChord(accuracy); // adjust field tracking accuracy
  }
  else fLocalFieldManager->SetDetectorField(NULL);
  G4bool forceToAllDaughters = true; // use field for daughter modules
    if(VolName=="top") forceToAllDaughters=false; // except for top volume which cover all other volumes
  lvciter->SetFieldManager(fLocalFieldManager, forceToAllDaughters);
}
```

MDISim - Geant4

Essential information -- directly available on MDISim level

- **root display of synchrotron radiation cones**
- **energy flow tables**

already set up to be complemented by full shower simulation



Geant4 tracking with synchrotron radiation generation and absorption --
directly from MDISim generated root geometry imported via gdml to Geant4
Test shown here shown here for a small (LEIR) geometry